UNDERWATER FLEXIBLE SHEAR-STRESS SENSOR SKINS

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ABSTRACT

This paper reports the development of underwater flexible shear-stress sensor skins that enable not only the acquisition of shear-stress distributions on non-planar surfaces but also a reliable packaging scheme. The sensor skin fabrication consists of two steps: the fabrication of shear-stress sensors on silicon wafers and the fabrication of flexible skins by forming arrays of silicon islands sandwiched by two polyimide layers. The fabricated sensor skin has been packaged on a metal plug and bonding pads were folded to the back side through a slit on the plug. Wire bonding was performed on the back side to improve the reliability and minimize flow interference. The packaged sensor skin has been installed on a water tunnel and successfully tested.

1. INTRODUCTION

Shear stress measurement is of crucial importance for many fluid dynamic monitoring applications [1]. In the past, we have concentrated on the development of sensors for applications in air, rather than in liquid (e.g. water) [2-6]. In MEMS02, we reported the development of rigid chip shear-stress sensors specifically for underwater applications [7]. As shown in Fig. 1, the sensor is a polysilicon resistor sitting on a nitride diaphragm with a vacuum cavity underneath, which provides excellent thermal isolation to reduce the heat loss to substrate. The input power of the resistor changes with the wall shear stress of the ambient fluid and this change can be readily detected electronically. The MEMS02 paper addressed two challenges for the underwater applications: the development of a compatible waterproof coating and the minimization of the sensors' pressure sensitivity. Nevertheless, there still exist two more challenges for the practical application of underwater shear-stress sensors. The first one is how to obtain shear-stress distribution on non-planar surfaces since it is usually the information on non-planar surfaces that is of interest. The packaging of the underwater sensors represents another challenge. Wire bonding or soldering on the front side is not desirable because this is not reliable and will introduce flow interference. This paper reports the development of flexible underwater shear-stress sensor skins that can overcome the two obstacles simultaneously.

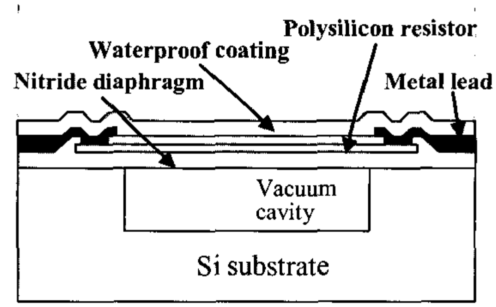

Figure 1: Cross section of the underwater shear-stress sensor.

2. FABRICATION

The fabrication process consists of two steps: the fabrication of shear-stress sensors and the fabrication of skin structures. As shown in Fig.2, the process starts with the deposition and patterning of a layer of low stress silicon nitride on silicon wafer. Cavities are then etched into silicon and refilled with local thermal oxidation (LOCOS). After the wafer is planarized by HF dip, 0.4 µm phosphosilicate glass (PSG) is deposited, densified, patterned, and annealed to form the etching channels for the cavities. Next, about 1.5 µm low stress nitride is deposited as the diaphragm and patterned to open the etch holes. Then the nitride diaphragms are released by etching away the underneath PSG and thermal oxide through etch holes using concentrated HF. After this, another nitride layer is deposited to reach the desired diaphragm thickness (4µm) and to seal cavities simultaneously. Next, 0.5 µm polysilicon film is deposited, doped, annealed, and patterned to form the sensing resistors. The dose of the boron ion implantation is $1 \times 10^{16}/cm^2$ that results in a boron concentration of $2 \times 10^{20}/cm^3$. The measured TCR of this heavily doped polysilicon is about 0.081%/°C. After another 0.2 µm nitride is deposited as a passivation layer, the contact holes are opened and a 1.5 µm thick aluminum layer is sputtered, patterned, and sintered. At this point, the fabrication of the sensors is finished. Figure 3 shows the SEM picture of one shear-stress sensor and Figure 4 illustrates two rows of sensors with different diaphragm widths, ranging from 75µm to 210µm. Note that the sensors are placed normal to each other in order to

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measure the direction as well as the shear stress of the flow.

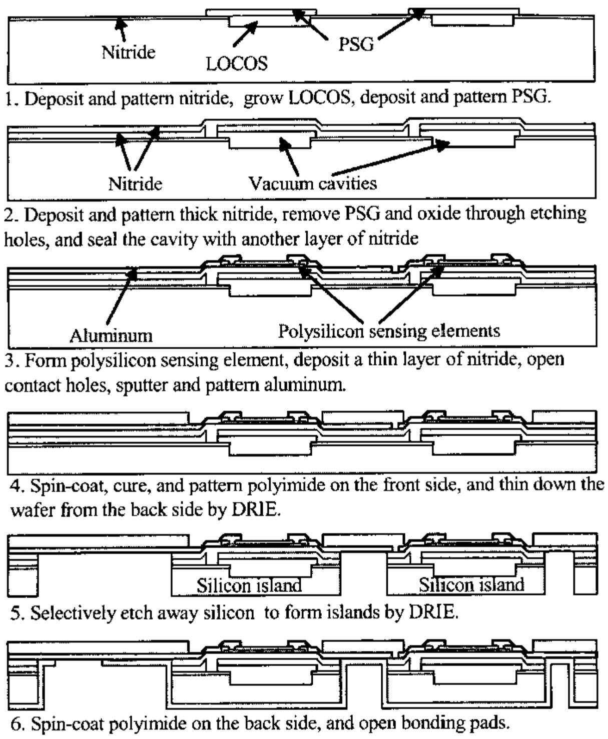

Figure 2: Simplified process flow of the underwater shear-stress sensor skin.

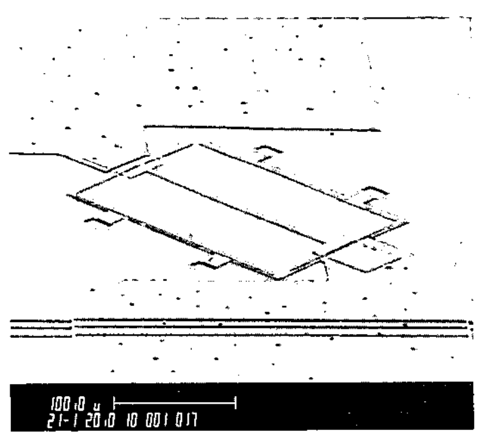

Figure 3: SEM picture of a shear-stress sensor.

The fabrication of skin structure starts with the coating of 6 μm polyimide on the front side, which helps to hold silicon islands during the backside etching process as shown in step 5 of Fig 2. The polyimide is then cured at 350 °C and patterned by oxygen plasma to expose the sensors. After the bulk silicon is thinned down to ~70 μm, the silicon islands are formed by selectively etching away the silicon between islands using DRIE. Note that further backside etching is needed to remove the nitride layer deposited on front side previously. After this, another layer of polyimide is spin-coated on the back side to encapsulate the silicon islands. Finally, polyimide is patterned to open the bonding pads. Note that the bonding pads can be opened on either front side or back side.

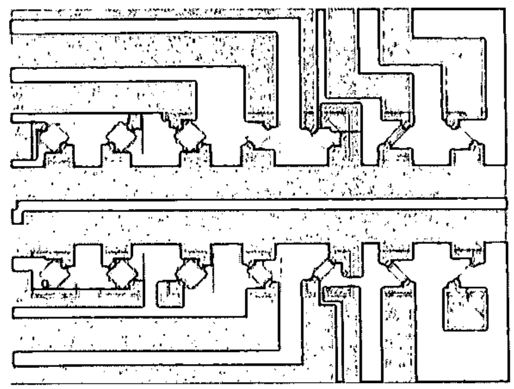

Figure 4: Two rows of shear-stress sensors on the rigid silicon wafer.

Figure 5 shows a micrograph of a portion of a fabricated sensor skin. By comparing Fig 4 and Fig 5, the relationship between rigid chip sensors and flexible sensor skin can be clearly observed. The sensor skin can be mounted on non-planar surfaces with a pixel size determined by the size of the silicon islands, which is 500 μm ×500 μm in this case.

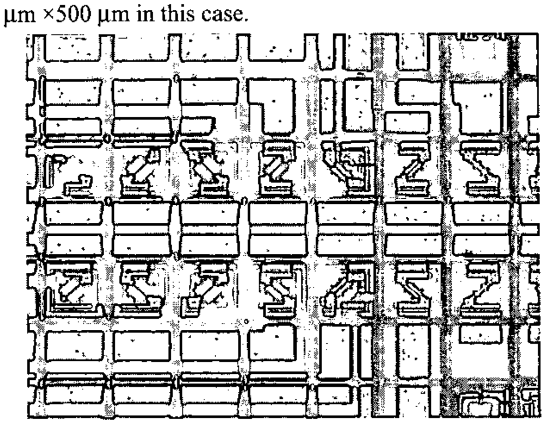

Figure 5: Two rows of shear-stress sensors on silicon islands that are sandwiched by two layers of polyimide.

The approach employed here to make flexible sensors is very different from the conventional method by depositing and patterning thin films on flexible substrates. Here we fabricate sensors on rigid silicon substrate first, then realize the skin structures by forming arrays of small silicon islands encapsulated by two layers of polyimide. The biggest advantage of this approach is its compatibility with current MEMS and IC technologies since MEMS devices and electronics can be fabricated on silicon wafers first. With this generic method, a variety of MEMS devices or electronics can be integrated into skins. This technology is developed based on the idea first reported by Barth et al. [8] and has been improved significantly since then [4, 6, 9]. One special challenge arises here due to the thick nitride layer (> 4 μm), which easily cracks because of the large tensile stress. This thick nitride layer has to be thinned down before releasing from back side. Otherwise this nitride layer will crack and break the aluminum wires on top of it. In Fig. 3, we can clearly observe the 3 steps caused by 3 consecutive thinning down processes performed right before sputtering aluminum. The reason to break the thinning down into 3 runs is to reduce the height of each step and alleviate the step coverage problem for aluminum metallization.

3. PACKAGING

The packaging is always a challenging problem for many MEMS applications, especially for this underwater shear stress measurement. As mentioned previously, wire bonding or soldering on the front side is not reliable and will introduce flow interference. With the flexile skin structure, a novel packaging scheme can be realized as depicted in Fig. 6. The sensors are mounted on the front side of a sensor plug while the metal leads of the sensor skin are folded to the back side through a slit on the plug. Electrical connections to the sensors can be made by wire bonding or soldering on the back side conveniently. With this method, the flow disturbance introduced is minimized and the reliability is improved by isolating the electrical connection from water. Figure 7 shows a picture of a sensor skin packaged on an aluminum plug with this scheme. The electrical wires coming from the back side of the plug can be observed. The whole package was then put in the parylene deposition chamber and coated with 2 μm parylene C that functions as a waterproof layer. Selective parylene deposition can also be employed at this step [10]. After this, the sensors are ready for testing. Note that for the testing purpose, the top surface of the sensor plug is flat. For real underwater applications such as the flow pattern measurement of torpedoes or radio controlled submarines, the sensor skin can be packaged on non-planar surfaces if desired. It is worth noting that the packaging scheme developed here can also be employed in many biomedical applications.

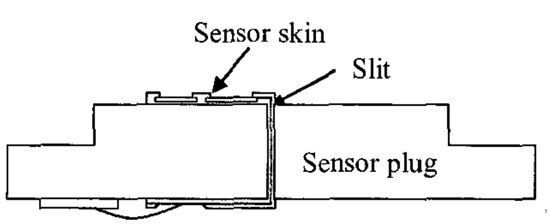

Figure 6: Packaging scheme based on the flexible skin structure.

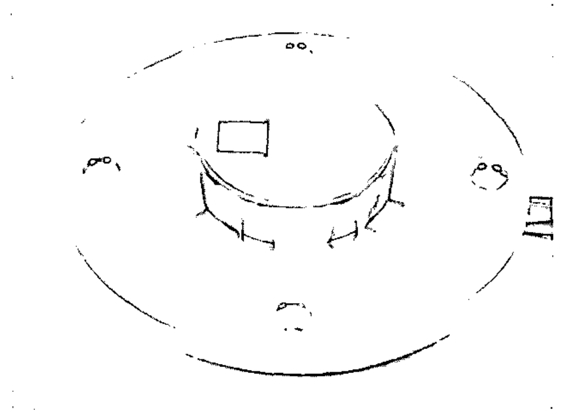

Figure 7: Sensor skin packaged on an aluminum plug.

4. TESTING

The packaged sensor skin shown in Fig. 7 has been installed in a water tunnel and tested. Figure 8 shows the picture of the Plexiglas water tunnel, consisting of an upstream reservoir, flow channel, downstream sink, and a recirculating pump. The tunnel is a close-loop system, designed to provide a known shear-stress environment for calibrating the shear-stress sensors.

During sensor testing, the sensor plug was inserted into a pre-cut hole in the top plate of the tunnel (refer to Figure 8). Since the thickness of the 1.5" mount where the sensor skin was attached matches the thickness of the Plexiglas plate, the sensors were flush with the top inside wall of the test section. The sensor plug was mounted at a distance of 40cm from the end of the contraction. This distance is equivalent to 40 channel heights and the fluid flow that the sensors encounter should therefore be fully developed.

The test section of the channel has a high aspect ratio of 20 to 1 (20 cm to 1 cm). As a result, fluid flow in the test section is expected to approach that of a two-dimensional channel flow. Under this condition, the surface shear stress can be calculated based on the volumetric flow rate by using the following relationships:

$$U_\tau / U_{av} = 0.109(\mathrm{Re})^{-0.089}$$

$$\mathrm{Re} = U_{av}(2h)/\nu$$

$$U_\tau = (\tau_w/\rho)^{0.5}$$

$$U_{av} = Q/A$$

where τ_w = surface shear stress, Q = volumetric flow rate, h=height of channel (1cm), ρ =density, ν =kinematic viscosity, A= cross sectional area, U_{av}= average velocity, and Re = Reynolds number.

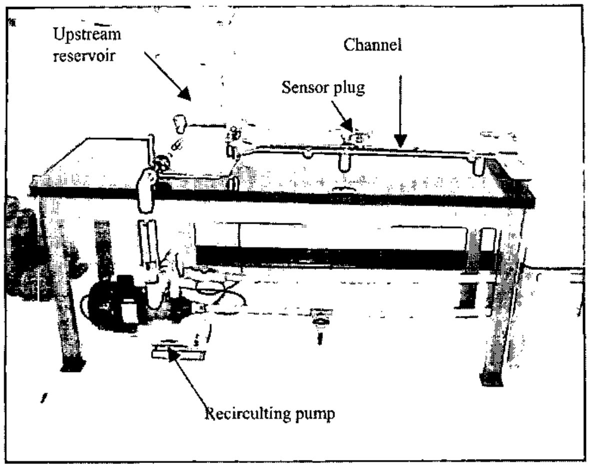

Figure 8: Picture of the water tunnel for the shear stress calibration

The highest volumetric flow rate that the recirculating pump can provide, without overflowing the upstream reservoir, is 40 GPM (gallon per minute) while the lowest is 18 GPM, corresponding to an average velocity of 1.25 m/s and 0.56 m/s, respectively, in the test section. This, in turn, corresponds to a shear stress of 3.1 Pascal and 0.71 Pascal, respectively.

Figure 9 shows a typical calibration curve of one shear-stress sensor, which operated in constant temperature mode with a working temperature 35°C above ambient water (with an over-heat ratio of 3%). Each data point was time-averaged. Note that the data have already been temperature compensated based on the temperature sensitivity calibration performed. Hysteresis was observed during the test (not shown in Fig. 9). This is possibly due to the imperfect temperature compensation or imperfect flowrate monitoring of the water tunnel.

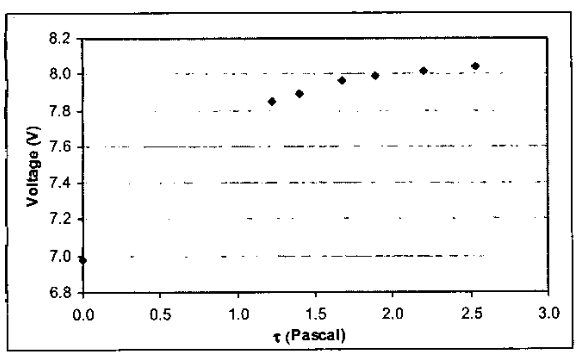

Figure 9: Calibration curve of one sensor on the skin.

5. CONCLUSION

Flexible shear-stress sensor skins for underwater applications have been successfully fabricated using a unique silicon-based flexible skin technology. One sensor skin has been packaged on a metal plug using a novel packaging scheme. The packaged sensor skin has been installed on a water tunnel and successfully tested. In conclusion, the underwater flexible shear-stress sensor skins enable not only the acquisition of shear-stress distributions on non-planar surfaces but also a reliable packaging scheme for underwater applications. This packaging scheme can be employed in many applications other than underwater shear stress measurement.

ACKNOWLEDGMENT

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